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Spectrum research on the passive mode-locked Yb^{3+}-doped fiber laser

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Abstract In this paper, the spectrum characters of passive mode locked Yb^{3+}-doped fiber laser were investigated in detail, tunable four wavelengths with more than 30 nm tuning range, single wavelength, double wavelengths, multi-wavelengths laser output have all been observed in experiment. Moreover, these results were analyzed theoretically.

Keywords Wavelength · Passive mode-locked · Yb^{3+}-doped fiber laser · Dispersion

1 Introduction

Stable multi-wavelength mode-locked fiber lasers are particularly useful in fiber-optical sensing, optical instrumentation, microwave photonic systems, optical signal processing, wavelength-division-multiplexing transmission systems and so on Pudo and Chen (2003), Lou et al. (2004), Chen et al. (2000), Gong et al. (2005), (2006), Li and Chan (1998), Yao et al. (2001), Hayahi and Yamashita (2003), Bellemare et al. (2000), Wey et al. (1997), Li et al. (1998), Vlachos et al. (2000), Mielke et al. (2003), Tu et al. (2007), Fenga et al. (2006), Yeh et al. (2007), Schultz et al. (2009), Okhotnikov et al. (2003), Kivist et al. (2008), Zhe et al. (2009), Song et al. (2009a), Song et al. (2009b), due to the numerous advantages including the generation of narrow high-repetition-rate pulse trains at multiple wavelengths, high power, low noise and the compatibility with other fiber-optic components.

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Many different mode-locked multi-wavelength fiber lasers have been reported in the last few years. Previously, room-temperature multi-wavelength lasing in an actively mode-locked erbium-doped fiber ring laser (ML-EDFRL) was demonstrated by use of multiple gain media in the laser cavity Pudo and Chen (2003), temporal-spectral multiplexing Lou et al. (2004), flattening the gain spectrum Chen et al. (2000),or the inter-channel multiple four-wave mixing Gong et al. (2005). However, these designs are somewhat complex or have poor tunability. As an alternative way, multi-wavelength dispersion-tuned actively ML-EDFRL has been proposed Li and Chan (1998). However, the laser is sensitive to the environment disturbance due to its long cavity. Further more, the erbium-doped fiber lasers were cooled in liquid Nitrogen to reduce the strong homogenous gain broadening effect at room temperature, Yao et al. (2001), Hayahi and Yamashita (2003), which made the system bulky and impractical for real applications. Bellemare et al. (2000) used a frequency shifter in a cw fiber lasers to reduce homogenous gain broadening. A variable cavity length created by introducing a frequency shifter may not be suitable for active mode locked. High noise is another problem for multi wavelength active mode locked fiber lasers. By using an intra-cavity F-P filter or a nonlinear polarization rotator Wey et al. (1997), Li et al. (1998), the supermode noise can be suppressed, but at the cost of high insertion loss. It was demonstrated that the use of semiconductor material as the gain medium could provide stable multi-wavelength lasing at room temperature with weaker homogenous gain broadening Vlachos et al. (2000), Mielke et al. (2003). However, lasers using semiconductor material tend to have low output power and high noise figure comparing with EDF-based lasers.

Contrast to active multi-wavelength mode locked fiber lasers, passive multi-wavelength mode locked fiber lasers have been a powerful technique for the generation of subpicosecond and femtosecond optical pulses. As it is self-starting, modulation mechanisms are not needed comparing with active starting, so the cost and complexity of the ultrashort pulse lasers reduce. Based on so many advantages, passive multi-wavelength mode locked fiber lasers have been widely studied by many people currently Tu et al. (2007), Fenga et al. (2006), Gong et al. (2006), Yeh et al. (2007). In order to generate multi-wavelength laser, all kinds of filters were used such as Mach–Zehnder filter Tu et al. (2007), F-P filter Fenga et al. (2006), polarization maintaining fiber filterGong et al. (2006) and double-ring filterYeh et al. (2007). In order to tune the wavelength, interference tunable spectral filter Schultz et al. (2009), grating-pair tunable dispersive delay line Okhotnikov et al. (2003) and acousto-optic tunable filter Kivist et al. (2008) have been used. A signal or dual wavelength tunable passive mode locked Erbium-doped Fiber lasers only by appropriately rotating the polarization controllers have been reported Zhe et al. (2009), Song et al. (2009a), Song et al. (2009b).

However, multi wavelength tunable passive mode locked Yb^{3+}-doped fiber laser only by appropriately rotating the polarization controllers has not been reported to our best knowledge. In this paper a tunable four wavelengths passive mode locked Yb^{3+}-doped fiber laser is obtained by only adjusting the polarization controller carefully and choosing the proper parameters of fiber laser. Moreover, single wavelength, double wavelengths, multi-wavelengths have been also observed and studied in this paper.

2 Principle and design

Schematic diagram of mode-locked system is shown in Fig. 1. Yb^{3+-}-doped fiber ring laser is composed by Yb^{3+}-doped fiber as gain medium(the absorption of Yb^{3+}-doped fiber for the pumping laser at 979 nm is 199 dB/m), polarization-dependent optical isolator (PD-ISO) as polarizer, two polarization controllers (PC_1 & PC_2), 980/1053 nm wavelength-division

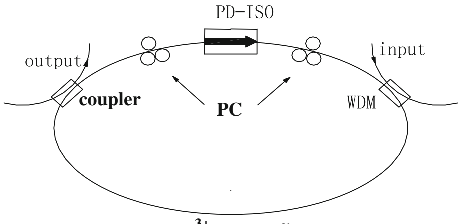


Fig. 1 Experimental setup of Yb^{3+}-doped fiber ring laser

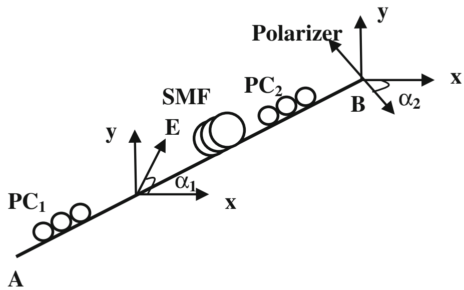


Fig. 2 Principle of NPR, E: Electric vector of input signal; x: fast axis of SMF; y: slow axis of SMF

multiplexer as signal and pump light coupler and the output coupler (90:10) as the signal light output. Pumping light source is two laser diodes operating at the wavelength of 976 nm with maximum output power about 440 mW. Pumping laser is coupled into Yb^{3+}-doped fiber by 980/1053nm wavelength division multiplexer.

In order to better explain the operation principle of the spectrum characters of passive mode locked Yb^{3+}-doped fiber laser, we analyze the light transmission character of the laser cavity which can be described as a length of fiber with two polarizers at both ends as shown in Fig. 2 Song et al. (2009b). α_1, α_2 are the angles between the input signal's polarization direction and the vertical birefringent axis, analyzer's polarization direction and the vertical birefringent axis respectively. Both α_1 and α_2 can be changed by adjusting the polarization controller PC_1 and PC_2. The PD-ISO plays the roles as both the polarizer and the analyzer. Then, the PC_1 transforms the light to an elliptical polarization state. The polarization state of the light rotates as it propagates in the cavity due to different effects of the self-phase modulation and cross-phase modulation on two orthogonal polarized components. The angle of rotation is proportional to the light intensity. Therefore, the combination of PC-PD-ISO-PC acts as a polarization-dependent loss controller. The transmittivity function T of this structure can be expressed as Song et al. (2009b):

$$T = \cos^2\alpha_1\cos^2\alpha_2 + \sin^2\alpha_1\sin^2\alpha_2 + \frac{1}{2}\sin 2\alpha_1\sin 2\alpha_2 \times \cos\left(\Delta\phi_L + \Delta\phi_{NL}\right) \tag{1}$$

$$\Delta\phi_L = \frac{2\pi L}{\lambda}\left(n_y - n_x\right) \tag{2}$$

$$\Delta\phi_{NL} = -\frac{2\pi L_1 n_2 P}{3A_{eff}\lambda}\cos 2\alpha_1 \tag{3}$$

Here, $\Delta\phi_L$ is the linear phase shift resulting from modal birefringence, $\Delta\phi_{NL}$ is the nonlinear phase shift caused by the effects of the SPM and XPM. n_x and n_y are the refractive indices of the respective fast and slow axes of the optical fiber. L_1 is the length of the optical fiber

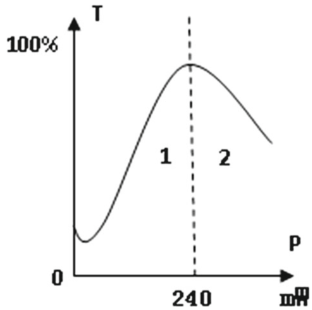


Fig. 3 The transmittivity(T) against light power(P) induced by NPR

between PC_1 and PC_2. λ is the operating wavelength, n_2 is the nonlinear coefficient, P is the instantaneous peak power of input signal, and A_{eff} is the effective fiber core area.

From Eq.(1) we can see that the system transmission depends on the linear phase shift due to modal birefringence and the nonlinear phase shift introduced by the nonlinear effects of SPM and XPM as reference Song et al. (2009b) discussed, in the case of different values of angle α_1 and α_2, the transmission of the fiber loop manifests as a trigonometric function of the operating wavelength and the instantaneous peak power. Consequently, the polarization -dependent loss of this system can be changed into wavelength- and intensity-dependent loss as Eq.(1) and Fig. 3. Lasers will emerge at different wavelengths from the round trip with different polarization states. Then lasers can oscillate and be tuned by adjustment of the PCs at multi wavelength. Mode locked laser can be achieved in certain values of α_1 and α_2 based on the principle of nonlinear polarization rotation (NPR) effect Song et al. (2009b).

Of course, the Yb^{3+}-doped fiber is a normal dispersion medium Okhotnikov et al. (2003), which is different to Er^{3+}-doped fiber, so it is impossible to create soliton pulse without dispersion compensating. Only the anomalous dispersion compensating components are introduced into the cavity, the dispersion can be balanced and soliton pulses can be achieved. It is to say the mode locked pulse is a chirp pulse in the region of normal dispersion when no dispersion compensating component used in ring cavity. In the same time, the interference effect of normal dispersion, SPM and XPM will affect the shape of optical spectrum as the follows experiment analysis.

3 Experimental results and anylsis

Through carefully adjusting the direction angles of the polarization controllers PC_1 and PC_2, Yb^{3+} fiber ring laser can operate with four wavelengths mode-locked modes from 1037.875 nm to 1071.729 nm shown in Fig. 9 continuously when the pumping power is 240 mW. Taking advantage of the intensity-dependent loss induced by the NPR effect which could be used to efficiently suppress the mode competition, the output four wavelengths pulses were stable at room temperature in our experiment.

The pulses have been monitored by a high-speed photodiode (home-made) and an oscilloscope (Model TEXTRONIX 2467) with bandwidths of 10GHz and 350MHz respectively, the corresponding spectrum has been monitored by ADVANTEST Q8384 optical spectrum analyzer. Fig. 4 is autocorrelation traces of the four wavelengths mode-locked signal monitored by autocorrelation device of home-made. From that, we can find that the pulse width is about 31.39 ps and the average output power is about 12.5 mW. As seen in Fig. 9, the spectrum of four wavelengths of mode-locked signal with more than 30 nm tunable range, although

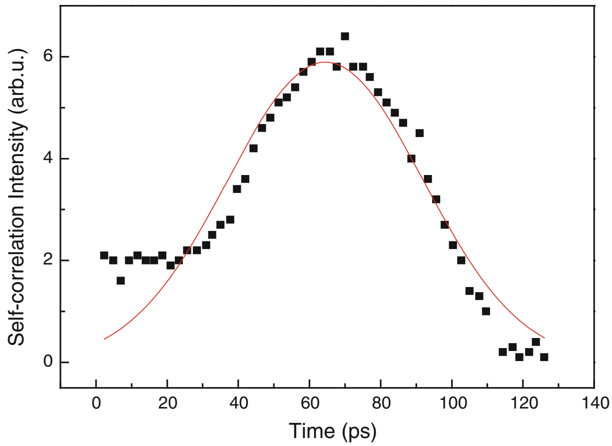


Fig. 4 Autocorrelation traces of the mode-locked signal with tunable four wavelengths (the dot line is experiment data and continuous line is Gaussian fit)

the side-mode suppression ratio of the output pulse is larger than 10 dB, the side-mode suppression ratio is very small compared with the side-mode suppression ratio of Er^{3+}-doped tunable dual-wavelength ultrashort pulse. Song et al. (2009b) We consider that the phenomenon is caused by interference effects between normal group dispersion and self(cross)-phase modulation.

In order to confirm this conclusion, we first decrease the pump power to weaken the self(cross)-phase modulation effect and carefully adjust the direction angles of the polarization controllers PC_1 and PC_2, the four wavelengths mode locked laser was never obtained and one or dual wavelength continuous laser have been obtained as Fig. 6 and Fig. 7, the side-mode suppression ratio of the output pulse exceed more than 40 dB, when the pumping power change to 240 mW, the continuous laser change to mode locked laser, we consider the transmittivity against light power induced by NPR is largest as shown in Fig. 3 in this time. In other way, when the cavity dispersion is compensated by grating compressor, pulse width will be compressed and the optical spectrum will be stretched as shown in Fig. 5 and 8. The central wavelength of the mode-locked pulse is 1053 nm and the spectral bandwidth (FWHM) is 27 nm. From Fig. 5, we can find that the pulse width is compressed to about 120.2 fs after introducing the grating chirp compressor. Moreover, the relative four wavelengths intensities of lasing wavelengths and the wavelength spacing were not accurately identical, this is because the operating pulses not only satisfy the mode locking condition but also the transmission function.

The single peak spectrum width can be expressed Jie et al. (2008) by formula (4) as follows when the multi peak spectrum as above four wavelengths is caused by interference effect between normal group dispersion and self(cross)-phase modulation.

$$\delta\lambda = \pm\lambda\sqrt{\frac{2m}{cD} - 0.0703\frac{\lambda^2}{(c\tau)^2}} \tag{4}$$

Where D is the cavity of passive mode locked Yb^{3+}-doped fiber laser, its value is 15 ps/nm, c is light velocity, m is integral number, τ is pulse width. Calculating by formula (4) using λ and τ are 1053 nm and 31.39 ps respectively, $\delta\lambda \approx 0.7$ nm, which is in good agreement with the experiment result as in Fig 9 $\delta\lambda \approx 0.67$ nm.

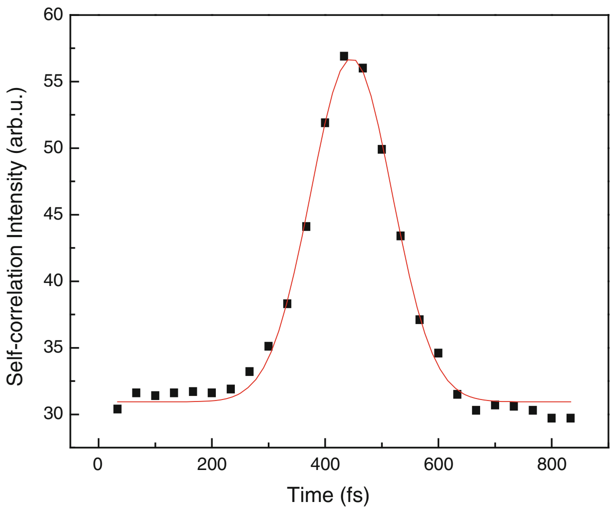


Fig. 5 Autocorrelation traces of the compression Mode-locked signal (the solid curve is Gaussian fit)

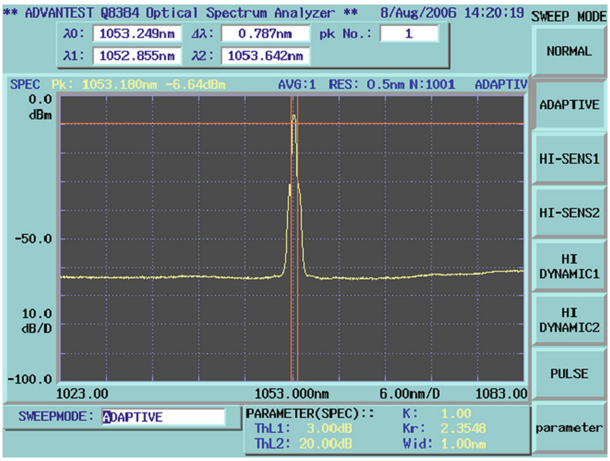


Fig. 6 Spectrum of single wavelength continuous laser

The interval of dual wavelength spectrum as in Fig. 7 can be expressed Song et al. (2009b) by formula (5):

$$\Delta\lambda = \frac{\lambda^2}{\Delta n L_2} \tag{5}$$

Here, Δn and L_2 are the average birefringence and cavity length of passive mode locked Yb^{3+}-doped fiber laser respectively, calculating by formula (5) using $\Delta n = 3 \times 10^{-6}$ and $L_2 = 10$ m respectively, then $\Delta\lambda \approx 36.9$ nm, which is in good agreement with the experiment result as in Fig. 7 $\Delta\lambda \approx 36$ nm. Single and dual-wavelength switching operation with different wavelength can also be achieved just through adjusting the PC_1 and PC_2.

In experiment, we carefully adjust the direction angles of the polarization controllers PC_1 and PC_2, multi-wavelength continuous laser are shown as Fig. 10 when the pumping power

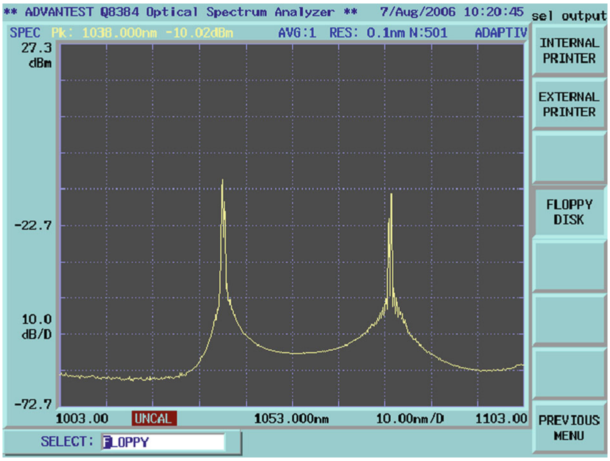


Fig. 7 Spectrum of dual wavelength continuous laser

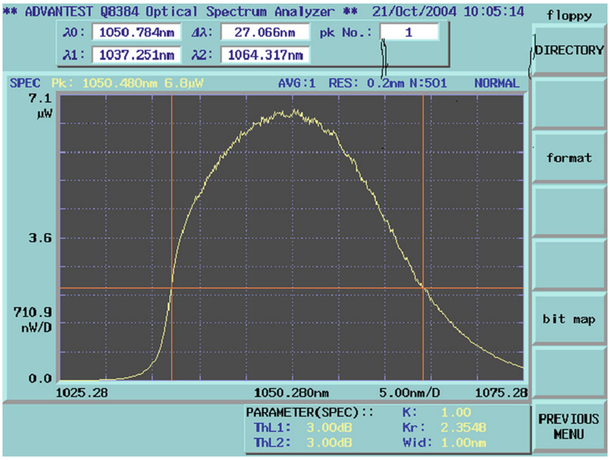


Fig. 8 Spectrum of mode-locked laser with chirping compensation

is larger than 300 mW. Moreover, we find the shape of the multi-wavelength spectrum is not only influenced by pump power, but also influenced by many factors such as the length of mode locked cavity, the length of Yb^{3+}-doped fiber, the coupling ratio of the output coupler and so on as reference Yu et al. (2009). We think in this case the transmittivity against light power induced by NPR is in the right region as shown in Fig. 3, for the inhomogeneous gain broaden effect of Yb^{3+}-doped fiber is obvious than Er^{3+}-doped fiber, so the multi-wavelength operating is more easily obtained for Yb^{3+}-doped fiber laser, the no-uniform amplitude of each wavelength is can be found in Fig. 10, which is caused by no-uniform of the Yb^{3+}-doped fiber's gain spectrum Jie et al. (2008).

For lower pumping power about 50 mW and 180 mW, the Q-switched mode-locked pulse and Q-switched pulse can be obtained respectively. The generation of Q-switched mode-locked or Q-switched pulse are influenced by pump power, direction angles of the polarization controllers PC_1 and PC_2 and so on Gan et al. (2006), Sanchez et al. (2008). The pump power

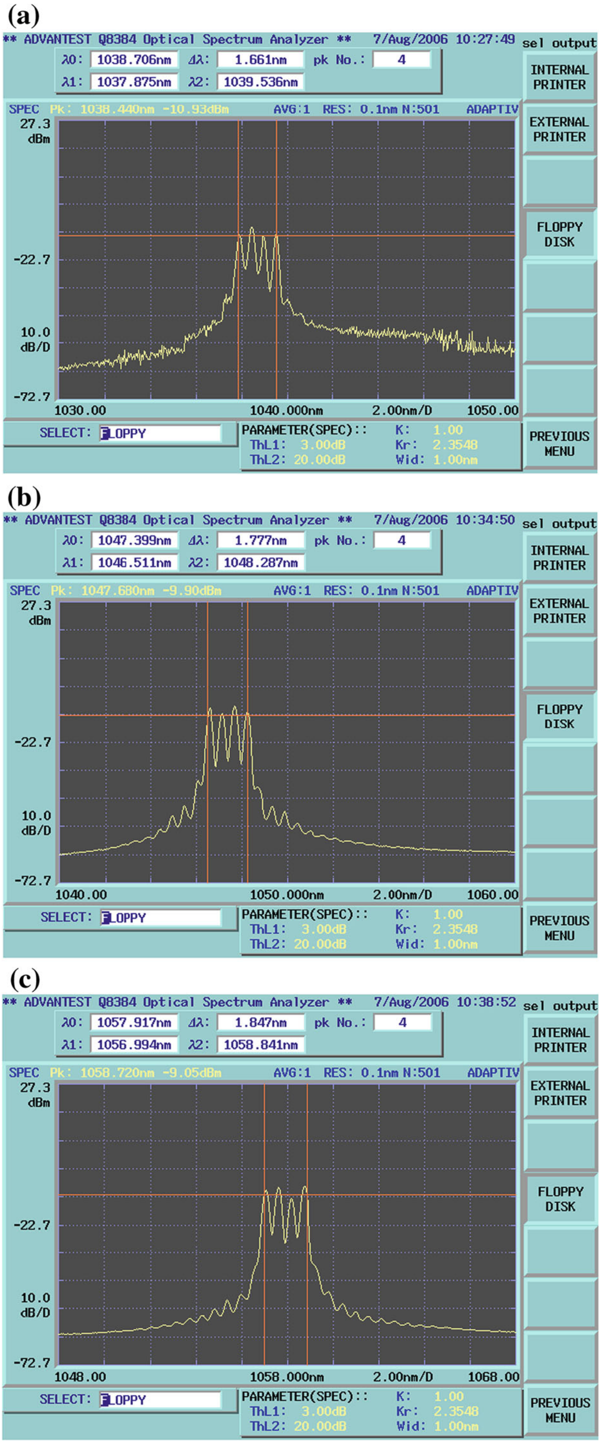


Fig. 9 (a,b,c,d as above four figures) Spectrum of tunable four wavelengths of mode-locked laser

Fig. 9 continued

(d)

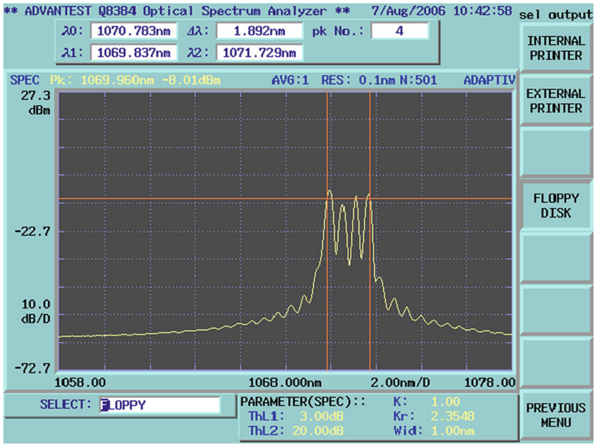
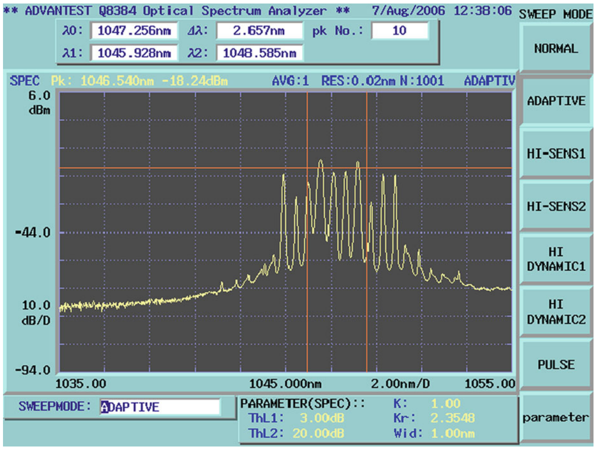


Fig. 10 Spectrum of multi-wavelength continuous laser



is more than 400 mW with two LD pumping, multi pulses phenomenon Komarov et al. (2006) has been observed. At the same time we observe the hysteresis phenomenon when the pump power decreases to the threshold of mode locked laser as reference Yu et al. (2009).

4 Conclusion

Tunable four wavelengths, single wavelength, double wavelengths, multi-wavelengths of passive mode locked Yb^{3+}-doped fiber laser were investigated in detail, tunable four wavelengths can be obtained only by adjusting the polarization controller carefully in the cavity and choosing the devise parameter of laser appropriately. The tuning range is more than 30 nm, The side-mode suppression ratio of the output pulse is larger than 10 dB. At the same time, single wavelength, double wavelengths and multi wavelengths have been all obtained, the experiment results are in good agreement with our theory analysis.

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